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Effect of Timber Harvesting on Stormflow Characteristics in Headwater Streams of Managed, Forested Watersheds in the Upper Gulf Coastal Plain of Mississippi

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Headwater streams are crucial parts of overall watershed dynamics because they comprise more than 50–80% of stream networks and watershed land areas. This study addressed the influence of headwater areas (ephemeral and intermittent) on stormflow characteristics following harvest within three first-order catchments in the Upper Gulf Coastal Plain of Mississippi. Four treatments including two Best Management Practices (BMPs) were applied: BMP1 – removal of all merchantable stems while leaving understory intact with minimum surface soil disturbance; BMP2 – same as BMP1 with the addition of logging debris to the drainage channel; Clearcut – total harvest with no BMPs applied; Reference – left uncut as a control. Following harvesting, the increase in water table depth ranged from 1.6 cm in BMP1 to 28.2 cm in the clearcut treatment during 2008, and from 10.5 cm in BMP1 to 54.2 cm in BMP2 during 2009. However, impacts of timber harvesting on peak discharge, storm discharge, and time of concentration were not consistent with water table response. Response time to stormflow was reduced significantly in harvested treatments (BMP2 and unrestricted harvest) probably as a result of decreased evapotranspiration and increased soil disturbance.

Key words: best management practices, ephemeral streams, headwater, stormflow, streamside management zone

INTRODUCTION

Headwater streams compose the uppermost portions of stream networks and typically represent the majority (50 to 80%) of the catchment area (Hansen, 2001; Benda *et al.*, 2005). Because of their higher topographic elevations and density within drainage basins, headwaters are important sources of water (Scanlon *et al.*, 2000; Winter, 2007), sediment (Benda and Dune, 1997; Hassan *et al.*, 2005; Macdonald and Coe, 2007), nutrients (McClain *et al.*, 2003; Moore and Wondzell, 2005; Alexander *et al.*, 2007), and materials (e.g. organic matter) (Kiffney *et al.*, 2000; Richardson *et al.*, 2005; Wipfli *et al.*, 2007). Connectivity refers to the water-mediated transport of matter, energy, or organisms within or between elements of the hydrologic cycle (Freeman *et al.*, 2007; Jackson and Pringle, 2010). In headwater systems, connectivity is often expanded during the wet season and during or after storm events, and the nature and degree of connectivity between headwaters and downstream reaches are ecologically significant in terms of the roles of headwater

streams (Gomi *et al.*, 2002).

Aquatic–terrestrial interfaces form a critical transition zone in landscapes which link adjacent ecosystems and control the movement of organisms, nutrients, materials and energy (Naiman and Décamp, 1997). Disturbances such as silvicultural practices on these boundary areas can impact all of the aforementioned processes within an ecosystem at local and landscape levels. However, the relationship between silvicultural practices in the uppermost portions of headwater systems (characterized by ephemeral drains) and linkages with downstream impacts is poorly understood.

The effects of timber harvesting on hydrologic responses of perennial streams have been well studied in the Southeastern United States (Ursic, 1991; Sun *et al.*, 2000, 2002; Swank *et al.*, 2001). Most studies have shown that changes in hydrologic response have been attributed to soil disturbance and reductions in evapotranspiration (Dietterick and Lynch, 1989; Lockaby *et al.*, 1997; Xu *et al.*, 2002). In general, timber harvesting tends to increase water yield, peakflow rates, and stormflow volume. The specific hydrologic responses are dependent upon site-specific conditions (climate, soil type, topography, and vegetation) as well as on the treatment applied (size and intensity). Timber harvesting can affect hydrologic responses in overland flow and subsurface flow dynamics either directly (through removal of vegetation, loss of evapotranspiration, and increase water yield) due or indirectly (through transport and accumulation of logging debris and associated changes in streamflow path). Timber harvesting also causes soil disturbances (e.g. compaction, rutting, and litter displacement) due to the use of harvesting equipment (Hutchinson and Moore,

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2000; Miwa *et al.*, 2004). This may result in changes to soil structure, subsurface flow and overland flow dynamics, increased water yield and higher peak flows during the first few years after harvesting.

However, hydrological, geomorphic, and biological processes in headwater streams differ markedly from those of larger streams (Moore and Wondzell, 2005; Anderson *et al.*, 2007). Because hillslopes and streams are tightly connected, material and energy transport within headwater systems are controlled by hillslope processes whereas material and energy routing in larger order streams is governed by the channel network (Gomi *et al.*, 2002). Additionally, headwater streams have smaller source areas and are more sensitive to natural droughts than are larger streams (Fritz *et al.*, 2008). Therefore, if headwater systems are evaluated based only on larger stream conditions (e.g. as in perennial streams), functions of intermittent and ephemeral drains are likely to be underestimated (Gomi *et al.*, 2002).

Over the past three decades, riparian management practices typically involve maintaining an unharvested riparian buffer around streams. It has been demonstrated that forested buffers are capable of reducing some adverse effects of timber harvesting on stream water and habitat quality (Lynch *et al.*, 1985; Ursic, 1991; Keim and Schoenholtz, 1999; Rivenbark and Jackson, 2004). Many states' forestry Best Management Practice (BMP) guidelines protect intermittent and perennial streams through forested buffers while ephemeral drains are often treated without distinction from adjacent upland forest. As such, most of the riparian research has been conducted on intermittent and perennial streams (Hughes and Cass, 1997; Carroll *et al.*, 2004; Vowell and Frydenborg, 2004). Moreover, most headwater studies have focused on downstream water quality issues associated with sediments, nutrients, and material transport

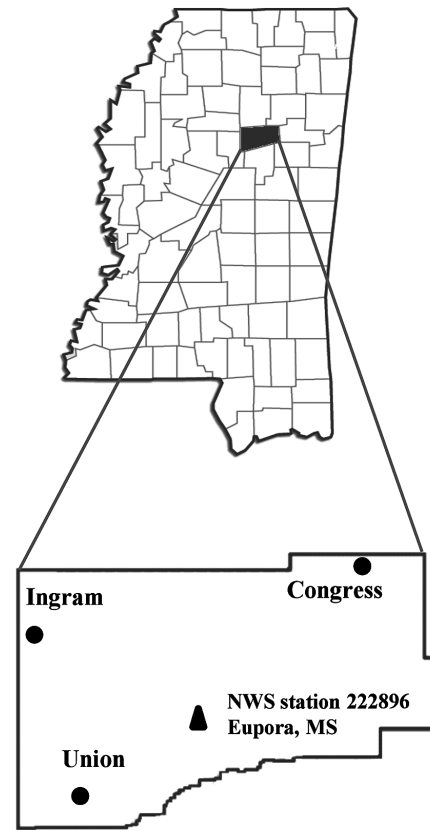


Fig. 1. Location map of study watersheds and weather station in Webster County, Mississippi.

even though there are indications that hydrology may affect the transport of these water quantity constituents.

This study examines the relationship between precipitation and stormflow in ephemeral–intermittent streams of first order catchments. This study includes one year of pre– and two years of post–harvest observations doc-

Table 1. Physical characteristics of study headwater streams in Webster County, Mississippi

Watershed	Treatment	Watershed area (ha)	Stream length (m) ^a	Stream gradient (%) Mean (min, max) ^b	Hillslope gradient (%) Mean (min, max)	Basal area removed (%) ^c
Union	BMP1	4.3	92	5(4, 6)	26(13, 39)	8.9
Union	BMP2	5.2	83	4(3, 5)	22(3, 42)	32.4
Union	Clearcut	4.4	81	4(3, 5)	26(14, 40)	70.1
Union	Reference	5.3	78	5(4, 5)	21(3, 39)	–
Congress	BMP1	4.8	117	5(4, 5)	15(2, 29)	28.1
Congress	BMP2	5.9	96	13(6, 19)	14(3, 31)	53.1
Congress	Clearcut	4.9	95	19(12, 22)	18(12, 30)	88.3
Congress	Reference	4.2	102	12(11, 13)	18(10, 40)	–
Ingram	BMP1	3.8	73	3(2, 4)	19(16, 24)	55.4
Ingram	BMP2	9.2	55	2(2, 3)	2(2, 3)	75.1
Ingram	Clearcut	5.2	85	5(4, 6)	16(10, 22)	95.2
Ingram	Reference	6.3	116	5(4, 6)	20(5, 29)	–

^a Stream length was a distance from the center well of the first measurement transect to the center well of 5th measurement transect.

^b Stream gradient was measured within measurement transects.

^c Values are approximate based on subsample within water table well transects.

umenting three potential management prescriptions for headwater areas. The objectives of this study were to (1) examine effects of timber harvesting on stormflow characteristics in ephemeral–intermittent streams and (2) test three silvicultural prescriptions for ephemeral–intermittent streams on stormflow characteristics.

METHODS

Site description

The study area comprises three first-order headwater catchments located in Webster County within the Sand–Clay Hills subsection of the Hilly Coastal Plain Province of Mississippi (Fig. 1). Study sites were chosen based on the presence of intermittent streams, forest land available for research, and similarity of vegetation, topography, and soils. We selected four watersheds within each catchment. The study area has a humid subtropical climate characterized by long, hot summers (May to October) and short, mild winters (December to February). Mean winter temperature is 7°C; mean summer temperature is 26°C (U.S. National Weather Service station 222896 Eupora, MS). Precipitation is well distributed throughout the year with a 30 year mean of 1,451 mm. Short and high intensity storms are common and storm precipitation can exceed 10 mm on occasions.

Watershed size ranged from 3.8 to 9.2 ha among the 12 watersheds. Stream gradients and hillslope gradients ranged from 2 to 19% and 2 to 26%, respectively, but both were generally consistent within catchments (Table 1). Soils were well to moderately well drained Sweatman (Fine, mixed, semiactive, thermic Typic Hapludults) and Providence (Fine–silty, mixed, active, thermic Oxyaquic Fragiudalfs) Series (McMullen and Ford, 1978). Soils within the rolling to ruggedly hilly area are high in clay content with A–horizons of either loam or silt loam. Hillslope water table typically drops to >2 m below the surface in the summer (Choi, 2011).

Study sites are in the Southeastern Mixed Forest Province (Bailey, 1983). Overstory vegetation is loblolly pine (*Pinus taeda* L.) of similar age with a lesser component of mixed hardwoods. Common hardwood species are yellow poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), American beech (*Fagus grandifolia* Ehrh.), black cherry (*Prunus serotina* Ehrh.), oak species (*Quercus* spp.), and hickory species (*Carya* spp.).

Study design and treatment

Twelve similar headwater streams with intermittent streams were selected for study and arranged in a completely randomized block design consisting of three blocks of four randomly assigned treatments (Table 1). The uppermost reaches (ephemeral drains) not governed by Mississippi's Forestry BMP guidelines (Mississippi Forestry Commission, 2000) received one of the following treatments: (1) BMP1 – removal of all merchantable stems greater than 15.2 cm diameter at breast height (DBH) leaving understory intact with minimum surface

soil and forest floor disturbance. Logging debris was prohibited in the drainage channel; (2) BMP2 – same as BMP1 with the addition of logging debris to the drainage channel in an attempt to decrease energy in the system and minimize head-cutting and continued channel development in the ephemeral area; (3) Reference – left uncut as a control; (4) Clearcut – total harvest with no BMPs applied within the drainage channels. Treatment boundaries were delineated using watershed contours in September 2007. Timber harvesting was conducted during October – December 2007, while surface soil conditions were dry using rubber tired feller–bunchers and grapple skidders.

Data collection

Fifteen-minute interval precipitation data across three years of study (from January 2007 to December 2009) were obtained from nearby U.S. National Weather Service station 222896 Eupora, MS (Fig. 1). Long-term (30 years) precipitation data were also obtained from the same station. At the junction of each intermittent flow segment and perennial stream, a 1.8 m length of 25.4 cm i.d. schedule 40 polyvinyl chloride pipe was installed and stabilized with sandbags to constrain flow (Fig. 2). Level and flow within the pipe were directly measured with area velocity sensors and flow loggers (ISCO 4150 area velocity flow logger, ISCO Inc., Lincoln, NE). Discharge was calculated using the stream depth and velocity data recorded at 15-minute intervals. Stream flow data were collected from January 2007 to December 2009. Three hundred screened wells were installed in grids of 25 per sub-watershed to monitor groundwater tables (Choi, 2011); groundwater wells were monitored on a monthly schedule from January 2007 to December 2009.

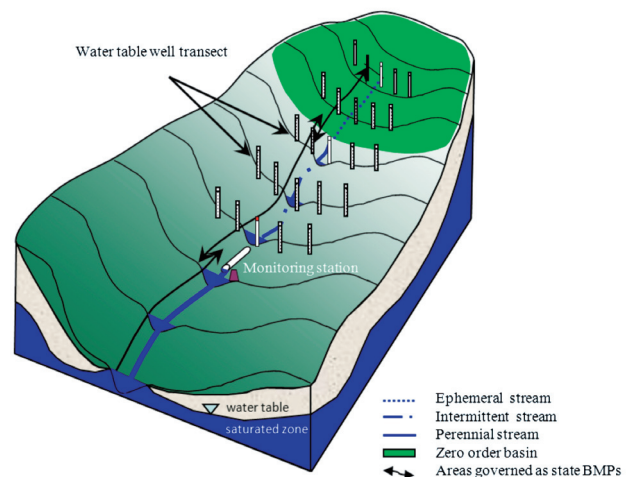


Fig. 2. Schematic of a study watershed with approximate location of stream, monitoring station, and water table well transects in headwater streams of Webster County, Mississippi.

Data analysis

Precipitation and streamflow data were analyzed to examine seasonal event precipitation and stormflow dynamics. We selected storm events based on peak flow

rates greater than $0.5 \times 10^{-3} \text{ m}^3/\text{s}$, total precipitation greater than 10 mm, and period between events greater than 48 hours. These criteria were arbitrarily selected to identify single peaked events and minimize influence of prior precipitation events on multiple peaks. A total of 39 storm events (7 for pre-harvest and 32 for post-harvest) were evaluated over three years using the aforementioned criteria. However, due to the variability among events in headwater streams and equipment failure, not all streams were sampled simultaneously and the number of collected storm events differed among streams. Stormflow characteristics including stormflow volume, peak flow rate, storm event duration, time of concentration (time from beginning of precipitation to peak discharge), and response time to stormflow (time from beginning of precipitation to measureable discharge) were calculated. Total storm precipitation was also calculated. Due to considerable seasonal differences in subsurface storage in the study watersheds, seasons were grouped as wet (November to April) and dry (May to October) based on monthly water table patterns.

Since precipitation and stormflow are causally related parameters, a simple linear regression analysis was used to determine the relationships between total storm precipitation and stormflow characteristics with respect to seasons. A completely randomized block (RCB) design was used to examine changes in the relationships between storm precipitation and stormflow characteristics following harvest.

$$Y_{ijk} = \mu + blk_i + trt_{ij} + t_k + trt_{ij} \times t_k + \varepsilon_{ijk} \quad (1)$$

$$(i = 1, \dots, 4; j = 1, \dots, 4; k = 1 \text{ or } 2)$$

where Y_{ijk} is the mean storm discharge, peak discharge, time of concentration, or response time to stormflow for treatment j in block i at time k . μ is the grand mean, blk_i is the random effect for block i , trt_{ij} is the fixed effect for treatment j in block i , t_k is a fixed factor for time k , where 1 represents the wet period and 2 represents the dry period, respectively. ε_{ijk} is the random error for treatment j in block i at time k .

We used the MIXED procedure of SAS (SAS Institute Inc., 2008) for all analyses. Total storm precipitation volume was a covariate for all analyses. A significant difference in a stormflow characteristic among treatments indicated that there was a significant difference in the regression slope describing the relationship between storm precipitation and the stormflow characteristic being tested. When main effects or interactions were significant, least square means were computed and comparisons were made using a significance level of $\alpha = 0.05$ and Tukey's adjustment.

RESULTS

Precipitation and antecedent water table condition

This study encompassed three years (one pre- and two post-harvest) with three distinct precipitation patterns. Annual precipitation for 2007 (pre-harvest) was

below-average at 1,001 mm (30-year mean=1,451 mm). Annual precipitation for 2008 (first year post-harvest) was roughly equal to the 30-year mean at 1,498 mm, however 28% of the annual precipitation for 2008 fell during the months of August and December (Fig. 3). The net result was that the study watersheds experienced a severe regional drought from February 2007 through December 2008 (National Drought Mitigation Center, <http://drought.unl.edu/dm/archive.html>). Annual precipitation for 2009 (second. year post-harvest) was 2,194 mm, the highest in the 25-year record in Webster County, Mississippi. While seasonal (dry and wet period) precipitation during 2007 and 2008 was similar, there were large seasonal differences during 2009 with precipitation during dry period (1,370 mm) being higher than precipitation during wet period (940 mm) (Fig. 3).

During the 2 years post-harvest, mean height of water table increased significantly in all the harvested treatments ($p < 0.001$) (Choi, 2011). Water table responses, however, were not solely due to timber harvesting, but rather a function of changing precipitation patterns pre- and post-harvest in combination with timber harvesting since similar patterns were observed within the reference (Fig. 3). Upon normalization of water table height by pre-harvest data, increases in water table height ranged from 1.6 cm in BMP1 to 28.2 cm in the clearcut treatment during 2008 and from 10.5 cm in BMP1 to 54.2 cm in BMP2 during 2009. Post-harvest seasonal responses of water table height were evident in that water table heights were more elevated during the normally dry period than during the normally wet period due to a

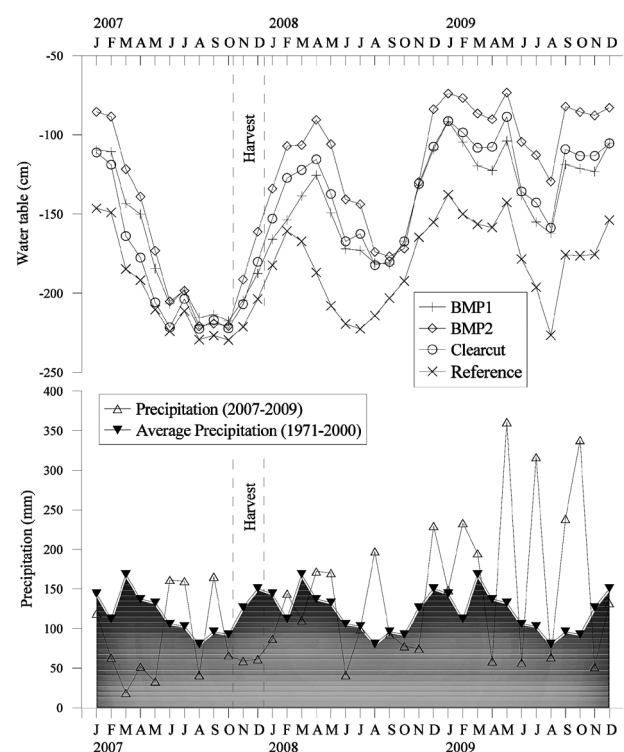


Fig. 3. Monthly treatment means of water table height and monthly precipitation in small headwater streams of Webster County, Mississippi.

reduction in evapotranspiration through the removal of overstory timber and consequent reduction in transpiration and interception loss (Choi, 2011).

Effects of timber harvesting on stormflow and peak discharge

Because storm precipitation and stormflow are related parameters, linear regression was used to examine changes in precipitation–stormflow relationships both pre- and post-harvest. There was no significant difference in either storm discharge ($p=0.584$) or peak discharge ($p=0.437$) among treatments pre-harvest. Post-harvest storm discharge ($p=0.118$ for wet and $p=0.897$ for dry) and peak discharge ($p=0.496$ for wet and $p=0.482$ for dry) showed no significant changes among treatments (Fig. 4). We also tested whether harvested treatments affected storm discharge using normalized values of storm discharge [(treatment value – reference value) / reference value], but did not detect any treatment effects. Post-harvest storm discharge for each storm event varied depending on season indicating that storm discharge follows seasonal water table position (Fig. 3 and Fig. 4); storm discharge ranged from 34 to 4163 m³ during the wet period and ranged from 46 to 436 m³ during the dry period. Post-harvest peak discharges showed little variability (0.005–0.052 m³/s for wet and 0.003–0.03 m³/s for dry period). Linear regression analyses revealed significant linear relationships between storm discharge and

storm precipitation during the wet period except for the BMP1 treatment (Fig. 4). Similar results were observed between peak discharge and storm precipitation during the wet period. During the dry period, treatment responses varied and only significant linear relationship ($r^2=0.29$; $p=0.006$) was derived between storm discharge and storm precipitation in the clearcut treatment (Fig. 4). Similar trends were found between peak discharge and storm precipitation during the dry period, but there was no significant linear relationship in all treatments. Higher variability observed during the dry period may be associated with characteristic high-intensity convective storms, increases in evapotranspiration rate following vigorous understory regrowth, and lower water table heights.

Effects of timber harvesting on time of concentration and response time to stormflow

Timing of stormflow was used to examine potential changes in the discharge time series after harvest. Pre-harvest period, there was no significant difference in either time of concentration ($p=0.731$) or response time to stormflow ($p=0.358$) among treatments. Following harvest, time of concentration did not change among treatments during either the wet ($p=0.381$) or dry ($p=0.159$) season.

On the other hand, there were significant differences in post-harvest response time to stormflow during both wet ($p=0.006$) and dry ($p=0.073$) periods due to the

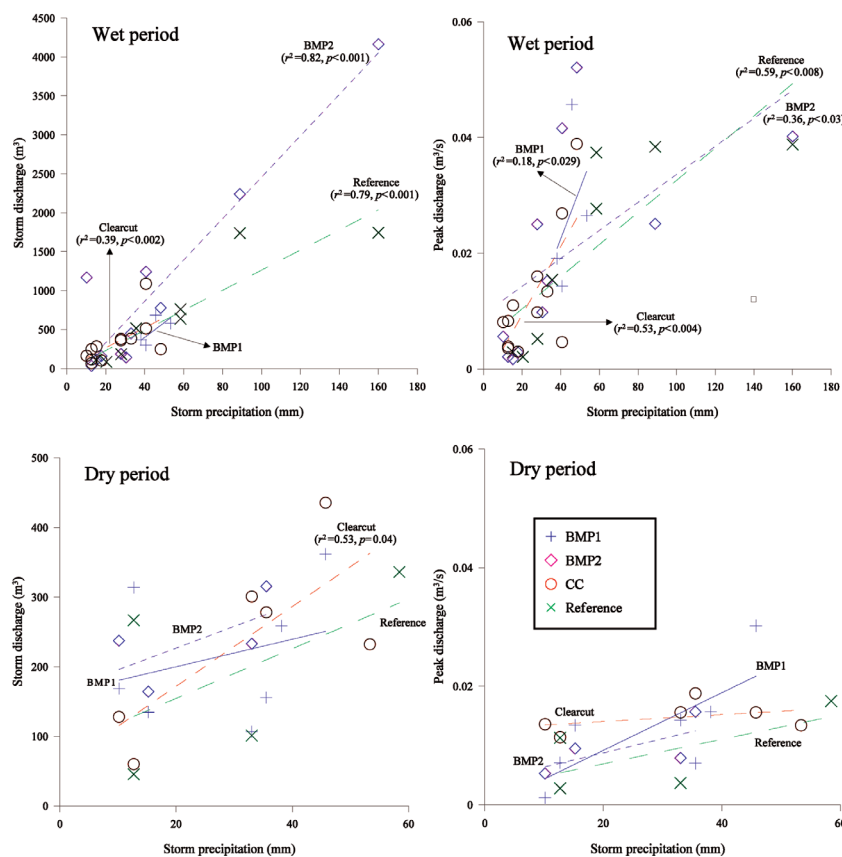


Fig. 4. Post-harvest seasonal relationships between storm discharge, peak discharge, and storm precipitation among treatments in small headwater streams of Webster County, Mississippi.

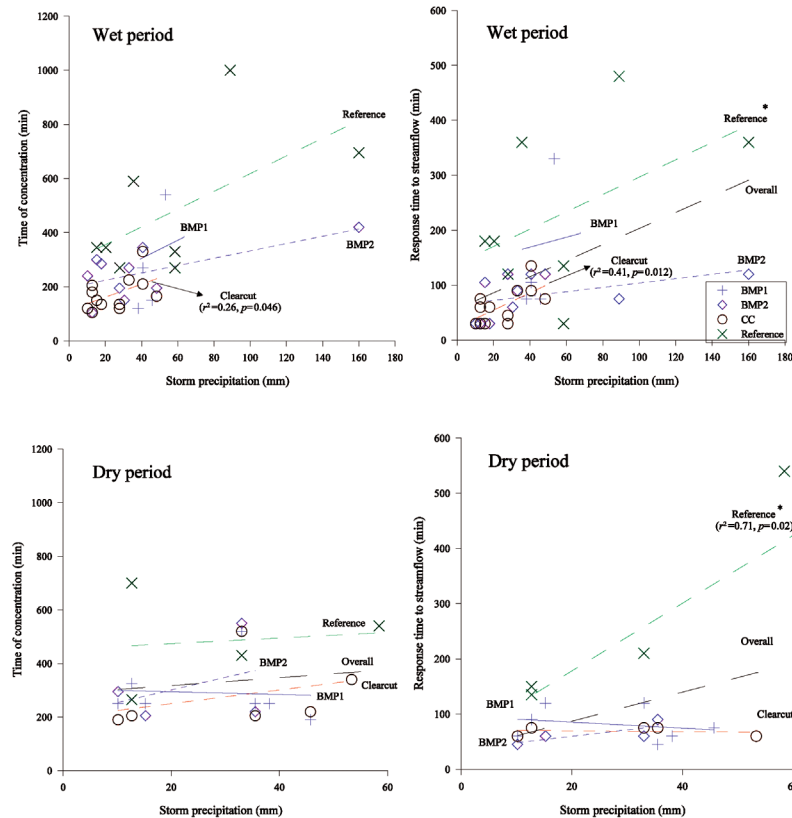


Fig. 5. Post-harvest seasonal relationships between time of concentration, response time to stormflow and storm precipitation among treatments in small headwater streams of Webster County, Mississippi.

*indicates significant differences among treatments at $\alpha = 0.05$.

impact of timber harvesting. During the wet period, post-harvest response time to stormflow was reduced in harvested treatments (BMP2 and clearcut) as compared to the reference treatment with no difference between BMP2 and clearcut treatment [BMP2 vs reference ($p=0.007$) and clearcut vs reference ($p=0.01$)] (Fig. 5). Similar results were found during the dry period, but differences were marginal [BMP2 vs reference ($p=0.06$) and clearcut vs reference ($p=0.05$)]. These results may indicate modified flow pathways in harvested treatment following harvest.

Post-harvest time of concentration varied depending on season ranging from 105 to 1305 minutes during the wet period and ranging from 190 to 700 minutes during the dry period. On the other hand, post-harvest response time to stormflow showed similar values [wet period (30–480 minutes) and dry period (45–540 minutes)]. Large seasonal differences in post-harvest time of concentration and little seasonal differences in post-harvest response time to stormflow reflect higher variability in event precipitation characteristics (e.g. amount, intensity, and duration) and differences in antecedent moisture conditions between two periods. The results show that there was only significant linear relationship between post-harvest time of concentration and storm precipitation during the wet period in the clearcut ($r^2=0.26$; $p=0.046$) treatment (Fig. 5). Similar results were found between post-harvest response time to storm-

flow and storm precipitation with a significant difference in the clearcut ($r^2=0.41$; $p=0.012$) treatment. During the dry period, no significant relationship ($r^2=0.02$; $p=0.26$) was observed between post-harvest time of concentration and storm precipitation, however there was a significant relationship between post-harvest response time to stormflow and storm precipitation ($r^2=0.71$; $p=0.02$) in the reference treatment (Fig. 5). Negative relationships during the dry period may be attributable to event precipitation characteristics (e.g. intensity and duration) or confounding effects that resulted from small number of storm events collected.

DISCUSSION

The impacts of timber harvesting on the hydrologic regime are of great concern in watershed management. Response of individual watersheds to timber harvesting is variable depending on site-specific conditions and on the treatment applied, however changes in hydrologic response are usually attributed to decreased evapotranspiration, soil disturbance, and road construction. We expected that storm discharge and peak discharge would increase after harvest due to reductions in evapotranspiration and increase in soil disturbance. However, this hypothesis was not supported by the present study. Although the results from this study suggest that there were generally good correlations between storm dis-

charge, peak discharge, and storm precipitation in all treatments, we did not find changes as a result of timber harvesting. Hornbeck (1973) observed that peak discharge increased up to 30% following harvest and storm discharge was three times higher during the growing season in a study of Hubbard Brook, New Hampshire. Swank *et al.* (2001) found that peak discharge and total storm discharge increased by 15 and 10%, respectively after clearcutting at Coweeta, North Carolina. These studies were conducted in perennial streams covering large catchments (60–100 ha) nearly an order of magnitude larger than watershed area in our study. Small watersheds as in the present study and large catchments may have different hydrologic responses. Therefore, caution should be exercised in direct comparisons between the present study and the earlier referenced work. In the present study, high climatic variability caused by prolonged drought during 2007 and 2008 combined with higher precipitation during 2009 may reduce our ability to determine differences between pre- and post-harvest observations. High natural variability in our small watersheds characteristics (e.g. size, soil, topography, and antecedent moisture condition) may also obscure treatment differences among treatments. In order to detect treatment differences in first-order headwater streams, larger watersheds (area harvested) may be needed due to the described temporal and spatial variability in climatic and watershed characteristics.

Response time and peak discharge of runoff from the beginning of event precipitation vary depending on precipitation characteristics and antecedent moisture condition. In the present study, the results show that timber harvesting did not affect time of concentration; however, response time to stormflow was reduced in harvested treatments (BMP2 and clearcut). This finding suggests that timber harvesting may result in more rapid stream flow response to precipitation in these study headwater streams through decreased evapotranspiration and increased water table height. The findings may also be attributed to modified flow pathways as a result of soil impacts (e.g. reduced infiltration capacity and increased bare soil area). Peak discharge after stream flow seemed to be a more complex process involving temporal and spatial variability of runoff generation (existence of pipe flow and streambed leaks) associated with precipitation characteristics and antecedent moisture.

CONCLUSIONS

This study investigated the changes in stormflow characteristics following timber harvesting in ephemeral-intermittent areas. The results showed that the height of water table increased up to 54.2 cm in harvested treatments, however impacts of timber harvesting on peak discharge, storm discharge, and time of concentration were not consistent with water table response. Nevertheless, response time to stormflow was reduced significantly in harvested treatments (BMP2 and clearcut) probably as a result of decreased evapotranspiration and increased soil disturbance. Therefore, downstream water quality

issues may be more related to soil disturbance caused by harvest operation rather than changes in water quantity following harvesting. However, connectivity expanded by increased water yield as a result of timber harvest may play a greater role in material transport to downstream reaches in these headwater streams.

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